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## The $X(3872)$ at CDF II

G. Bauer

(Representing the CDF II Collaboration)

*Laboratory of Nuclear Science, Massachusetts Institute of Technology,  
 77 Massachusetts Avenue, Cambridge, MA 02139, USA*

Last year's  $X(3872)$  discovery was confirmed with the CDF II detector in  $\bar{p}p$  collisions. We measure its mass to be  $3871.3 \pm 0.7 \pm 0.4$  MeV/ $c^2$ . The source of  $X$ -mesons in the large CDF sample is resolved by studying their vertex displacement. We find  $16.1 \pm 4.9 \pm 2.0\%$  of our  $X$ -sample comes from decays of  $b$ -hadrons, and the remainder from prompt sources: either direct production or by decay of (unknown) short-lived particles. The mix of production sources is similar to that observed for the  $\psi(2S)$  charmonium state.

*Keywords:*  $X(3872)$ ; Charmonium.

At last year's Lepton-Photon Symposium Belle announced discovery of a charmonium-like state,<sup>1,2</sup>  $X(3872)$ , in  $B^+ \rightarrow K^+ J/\psi \pi^+ \pi^-$ . CDF quickly confirmed  $X \rightarrow J/\psi \pi^+ \pi^-$ .<sup>3</sup> A natural interpretation of the  $X$  is the  $^3D_2$  of  $c\bar{c}$ , but this is contrary to expectations. The  $^3D_2$  is thought to be significantly lighter ( $\sim 3830$  MeV/ $c^2$ ); and Belle failed to detect decays to  $\chi_{c1} \gamma$ , which should be prominent for  $^3D_2$ . More circumstantial is the expectation of a relatively flat dipion mass ( $M_{\pi\pi}$ ) distribution for  $D$ -states,<sup>4</sup> whereas Belle found high masses preferred—possibly consistent with the (isospin violating) decay to  $J/\psi \rho^0$ . These difficulties, coupled with the proximity of the  $X(3872)$  to the  $D^0 \bar{D}^{*0}$ -threshold, prompted speculation that the  $X$  may be a  $D^0 \bar{D}^{*0}$  “molecule.” Whether this is the case, or the  $X$  is “only” a  $c\bar{c}$ -state in conflict with current theoretical models, the  $X$  is an interesting object of study.<sup>5</sup>

CDF II<sup>6</sup> is a general purpose detector at Fermilab's  $\bar{p}p$  collider. We use 220 pb<sup>-1</sup> of  $\mu^+ \mu^-$  triggers, yielding a clean  $J/\psi$  sample. Aside from technical cuts, kinematic and spatial cuts suppress large backgrounds from  $J/\psi$ 's plus random tracks. The main cuts are: a maximum number of  $J/\psi \pi \pi \pi$  candidates/event,  $p_T(J/\psi) > 4$  GeV/ $c$ ,  $p_T(\pi) > 400$  MeV/ $c$ , and  $\Delta R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.7$  for each pion, where  $\Delta\phi$  ( $\Delta\eta$ ) is the azimuthal (pseudorapidity) difference of the pion with respect to the  $J/\psi \pi \pi \pi$ . With these cuts a significant  $X$ -signal is revealed.<sup>3</sup> Here, however, we show in Fig. 1 the results split up into  $M_{\pi\pi} < 500$  and  $> 500$  MeV/ $c^2$  subsamples. No  $X$ -signal is apparent for low  $M_{\pi\pi}$ , supporting Belle's observation of high-mass decays.

Using the high- $M_{\pi\pi}$  sample, the  $X$ -mass is  $3871.3 \pm 0.7 \pm 0.4$  MeV/ $c^2$ . Also shown in Fig. 1 are masses from other experiments, and the average compared to the  $D^0 \bar{D}^{*0}$  threshold. The near equality helps fuel molecular- $D^0 \bar{D}^{*0}$  speculations.

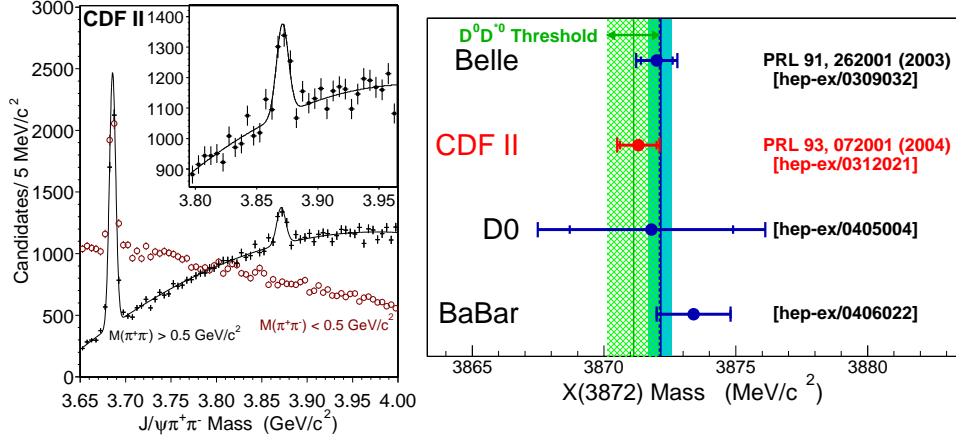


Fig. 1. **LEFT:** The  $J/\psi\pi^+\pi^-$  mass distribution for  $M_{\pi\pi} < 500$  and  $> 500$   $\text{MeV}/c^2$  subsamples. **RIGHT:** Summary of  $X$ -mass measurements compared to the  $D^0\bar{D}^{*0}$  threshold.

From Belle’s observation,  $B$ -mesons are a significant source of  $X$ ’s. This raises some questions: Is the CDF sample only from  $b$ -hadrons? If not, is direct  $X$  production different from charmonium? The technique of separating  $b$ -decay feeddown from prompt sources is well established.<sup>7</sup> Since  $X$ -decay is not weak, it is too rapid to leave a displaced vertex. If, however, it is produced by a (boosted)  $b$ -decay, the  $X$  will be displaced due to the  $b$ -lifetime. We measure the transverse  $X$ -displacement,  $L_{xy}$ , and convert it to an “uncorrected” proper-time:  $ct = M \cdot L_{xy} / p_T$ . This is not the true proper-time of the  $b$ -decay because  $M$  and  $p_T$  are only for the  $J/\psi\pi^+\pi^-$ .

We use the same  $X$ -sample as above, but now impose additional cuts related to the  $Si$ -vertex tracker, mainly to demand  $\sigma(L_{xy}) < 125 \mu\text{m}$  and have good beamline information. The sample is reduced by  $\sim 15\%$ . An unbinned likelihood fit is performed simultaneously over the  $ct$  and mass of the candidates. The signal is modeled by a Gaussian in mass; and for the  $ct$ -distribution, a resolution smeared exponential for the long-lived component and by the resolution function for the prompt. The background model uses a quadratic polynomial for mass, and resolution function for the prompt and *three* resolution smeared exponentials—one for the negative- $ct$  tail and two for the positive. The resolution function consists of two Gaussians.

The fit for  $\psi(2S)$  is shown in Fig. 2, where  $28.3 \pm 1.0 \pm 0.7\%$  of signal is displaced, similar to Run I results.<sup>7</sup> For  $X(3872)$ , with  $M_{\pi\pi} > 500$   $\text{MeV}/c^2$ , the fraction is  $16.1 \pm 4.9 \pm 2.0\%$  (Fig. 3)—a bit more than  $2\sigma$  from the  $\psi(2S)$ . These fractions agree with those obtained by simple sideband subtraction. They are, however, uncorrected for efficiency, and must be considered sample specific.<sup>7</sup> The *absence* of a  $b$ -component is excluded at  $3\sigma$  based on Monte Carlo “experiments.” Thus our  $X$ -sample is mainly prompt—presumably direct production—with a modest  $b$ -contribution.

It has been argued that all conventional  $c\bar{c}$  assignments for the  $X(3872)$  are

Fig. 2. Projection of  $\psi(2S)$  likelihood fit onto the uncorrected proper-time distribution for the full PDF, and its breakdown into signal (shaded) and background (hatched) classes. Signal and background are further separated into prompt and long-lived components. The projections are for candidates within  $\pm 2.5\sigma$  of the  $\psi(2S)$  mass in order to be reflective of its signal-to-background ratio. The fit actually spans the mass range 3640-3740  $\text{MeV}/c^2$ .

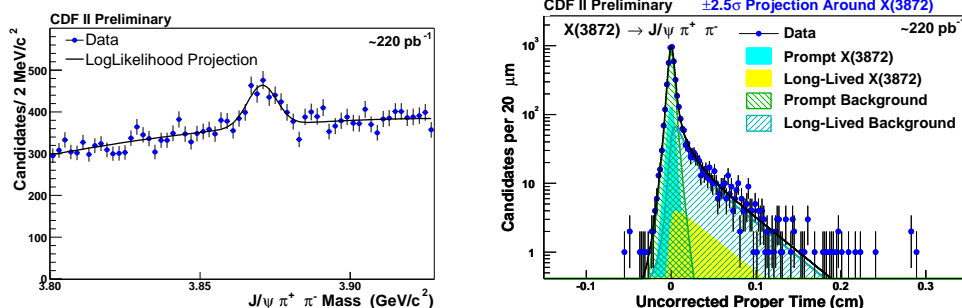


Fig. 3. Projections of  $X$ -likelihood fit in mass (left), and uncorrected proper-time (right) as Fig. 2.

problematic.<sup>8</sup> However, production of the  $X$  appears, so far, quite similar to that of the  $\psi(2S)$  in CDF. If it is indeed a “molecule,” there seems to be no dramatic penalty for producing such a fragile state in  $\bar{p}p$  collisions. Although, more incisive comparisons require specific theoretical models for the production of exotic states. A recent analysis of  $X$ -production as a  $1^{++}$  state<sup>9</sup> may benefit from our results.

Studies of this mysterious state are continuing in CDF.

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